RADIATION INDUCED WARPING OF PROTOSTELLAR ACCRETION DISKS

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ABSTRACT

We examine the consequences of radiatively driven warping of accretion disks surrounding pre-main-sequence stars. These disks are stable against warping if the luminosity arises from a steady accretion flow, but are unstable at late times when the intrinsic luminosity of the star overwhelms that provided by the disk. Warps can be excited for stars with luminosities of around $10L_{\odot}$ or greater, with larger and more severe warps in the more luminous systems. A twisted inner disk may lead to high extinction towards stars often viewed through their disks. After the disk at all radii becomes optically thin, the warp decays gradually on the local viscous timescale, which is likely to be long. We suggest that radiation induced warping may account for the origin of the warped dust disk seen in Beta Pictoris, if the star is only $\sim 10-20$ Myr old, and could lead to non-coplanar planetary systems around higher mass stars.

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1. INTRODUCTION

A geometrically thin, optically thick accretion disk is unstable to self-induced warping when illuminated by a sufficiently strong central radiation source (Pringle 1996; Maloney, Begelman & Pringle 1996; see also Petterson 1977). For a steady accretion disk, generating luminosity with an efficiency $\epsilon = L/\dot{M}c^2$, the instability can readily be shown to be important for disks around neutron stars and black holes, where it is generally assumed that $\epsilon \sim \mathcal{O}(0.1)$, provided only that the inner regions of such disks are not advectively dominated. Previous authors have discussed the implications of the instability for X-ray binaries, the masing disk in NGC4258 (Maloney, Begelman & Pringle 1996; Maloney & Begelman 1997), and the Unified Scheme for Active Galactic Nuclei (Pringle 1997). For disks around less compact objects, where ϵ is orders of magnitude smaller, steady disks are predicted to be stable.

The conclusion that the warping instability is unimportant for disks around white dwarfs, or ordinary stars, can be evaded if the luminosity of the central source greatly exceeds that provided by accretion. The disk then sees a radiation source much more powerful than that implied by the local accretion rate, and can be warped in the same way as a disk around a more compact body. Even if the luminosity *is* generated solely by accretion, a mass flux that is a strongly decreasing function of radius could allow the outer parts of a disk to be warped by the stronger radiation emitted from the inner disk. Such a scenario might be important in outbursting systems such as dwarf novae and FU Orionis stars, where the disk may be subject to thermal instability.

In this Letter, we apply the warping instability to accretion disks surrounding pre-main-sequence stars. In §2 we show that these disks are stable against warping during the main phase of steady disk accretion, but become unstable at late times when the surface density and accretion rate fall to low values. In §3 we apply our results to β Pictoris, which has been observed to be surrounded by a warped dust disk (Burrows et al. 1995), and show that this warp is consistent with a radiative origin. In §4 we present a numerical calculation of the excitation and subsequent decay of the warp. Our conclusions are summarized in §5.

2. WARPS IN PROTOSTELLAR DISKS

2.1. Conditions for the warping instability

The conditions under which a thin accretion disk, optically thick to absorption and re-emission of radiation, is unstable to radiation induced warping are derived in Pringle (1996) and Maloney, Begelman & Pringle (1996). Defining the timescales for the viscous and radiation torques as,

$$t_{\nu_2} = \frac{2R^2}{\nu_2}, \quad t_\Gamma = \frac{12\pi\Sigma R^3\Omega c}{L_*}, \tag{1}$$

instability occurs when the ratio,

$$\frac{t_\Gamma}{t_{\nu_2}} < \gamma_{\rm crit}. \tag{2}$$

Here L_* is the luminosity of the central source, Σ the disk surface density, Ω the Keplerian angular velocity, and ν_2 the (R, z) component of the disk viscosity. We note that ν_2 need not be equal to the more familiar (R, ϕ) component of the viscosity ν_1 (e.g. Pringle 1992), and we denote the ratio as $\eta = \nu_2/\nu_1$. In an earlier paper (Pringle 1996) $\gamma_{\rm crit}$ was estimated to be $\sim 1/2\pi$, and this is consistent with the numerical calculations in §4.

For radii much greater than the stellar radius, R_*, $\nu_1\Sigma = \dot{M}/(3\pi)$. From equation (2), the luminosity required to warp the disk at radius R is then,

$$L_* \gtrsim \frac{2\dot{M}\eta R\Omega c}{\gamma_{\rm crit}}. \tag{3}$$

If this luminosity is provided by the accretion disk and boundary layer, then $L_* \simeq GM_*\dot{M}/R_*$, and for a solar mass star the critical radius beyond which the disk will be unstable to warping is,

$$R \gtrsim 3.5 \times 10^5 \ \eta^2 \left(\frac{R_*}{R_\odot}\right)^2 \ {\rm a.u.} \ \gg R_{\rm disk}, \tag{4}$$

taking $\gamma_{\rm crit} = 1/2\pi$. Steady protostellar disks are therefore, as expected, stable against warping induced by their own luminosity.

If the luminosity is *not* provided by the accretion flow, equation (3) implies,

$$R \gtrsim 3 \ \eta^2 \left(\frac{M_*}{M_\odot}\right) \left(\frac{\dot{M}}{10^{-9} \ M_\odot {\rm yr}^{-1}}\right)^2 \left(\frac{L_*}{10 \ L_\odot}\right)^{-2} \ {\rm a.u.} \tag{5}$$

Typical accretion rates in pre-main-sequence T Tauri stars are $\sim 10^{-7} - 10^{-8} \ M_\odot{\rm yr}^{-1}$, so with $L_* \sim 10 L_\odot$ this implies that $\dot{M}$ needs to fall by 1-2 orders of magnitude before the inner parts of the disk become potentially unstable to warping. A large value of η at a few a.u. would suppress the instability. Whether warping occurs will then depend on the growth rate of the instability and, critically, on whether the disk remains optically thick to re-emission of intercepted stellar radiation. At radii where the disk is optically thin the re-emitted flux will be isotropic, so that there is no radiation torque or possibility for a warp to develop. At large radii of $\sim 10^2$ a.u. and greater, protostellar disks are known to be optically thin in the mm emission characteristic of those radii, but the inner few a.u. are likely to be extremely optically thick. Models for FU Orionis outbursts, for example, suggest that typical disks around solar type stars have a Shakura-Sunyaev viscosity parameter $\alpha \ll 1$ in the very innermost regions (Bell & Lin 1994), with correspondingly high optical depths. At radii where dust remains present, the implied surface densities suggest that the disks will become unstable to warping in their inner regions before they become optically thin.

For more massive Herbig Ae-Be stars, with higher luminosities, the critical accretion rate below which warping occurs will be greater. We would thus not *expect* to observe flat passive

(reprocessing) disks around stars of $M_* \gtrsim 2\ M_\odot$, as these would be destroyed by the action of the twisting instability. This could lead to a substantial fraction of systems where the star was viewed *through* the warped disk, displaying high extinction at short wavelengths.

2.2. Growth and decay timescales

The growth rate of the instability is $\sim t_\Gamma$ (Pringle 1996). Equation (1) yields an estimate for the growth time,

$$t_\Gamma \simeq 4 \times 10^3 \left(\frac{M_*}{2M_\odot}\right)^{1/2} \left(\frac{R}{3 \text{ a.u.}}\right)^{3/2} \left(\frac{L_*}{10\ L_\odot}\right)^{-1} \left(\frac{\Sigma}{1 \text{ gcm}^{-2}}\right) \text{ yr.} \tag{6}$$

A surface density in gas, $\Sigma = 1$ gcm^{-2}, corresponds roughly to $\tau \sim 1$ using a typical dust opacity at 100 μm (Menśhchikov & Henning 1997), and a standard gas to dust ratio of 100. This timescale is evidently much shorter than both the typical lifetime of a pre-main-sequence disk, which is a few Myr (Strom 1995), and the estimated disk dissipation timescale of $\sim 10^5$ years (Wolk & Walter 1996).

Equation (6), together with the instability criterion, equation (5), specify the qualitative development of warping in protostellar disks. Radii smaller than the critical radius, or so large that the disk is always optically thin to re-emission of stellar radiation, are stable. At all unstable radii, the strongest warping is expected when the surface density is lowest, just before the disk becomes optically thin. How far the warp is able to develop then depends on the time available before the annulus becomes optically thin, which to order of magnitude will just be the viscous time *of the disk*. The *local* viscous time will be shorter, but it is the viscous time of the entire disk that is relevant as this is the timescale on which $\dot{M}$, and hence also Σ decays. The strongest twisting will occur in the inner disk, both because t_Γ is smallest for the unstable modes there, and because inflow through the disk can advect an outer warp to smaller radii.

After a given annulus in the disk has become optically thin, radiative forcing of the warp ceases. The twist will then decay on the viscous timescale of the disk, spreading as it does to larger radii than the originally unstable region. If the original twist is severe, many viscous times may be required to flatten the inner and outer parts of the disk into the same plane. The decay timescale itself is likely to be long, as the viscous timescale is already ~ 1 Myr when there is still a significant amount of gas present, and thus the disk could retain a modest warp for a lengthy period after radiative excitation of the warp had ceased.

3. ESTIMATES FOR A β PICTORIS PROGENITOR

In this Section we consider β Pictoris, which is observed to be surrounded by a dust disk. *Hubble Space Telescope* observations show that the inner (few 10's of a.u.) region of the disk is warped by several degrees with respect to the outer disk (Burrows et al. 1995), and we examine whether a warp of this extent could arise from a radiatively driven mechanism.

For the stellar parameters, we follow Lanz, Heap & Hubeny (1995), and take a mass $M_* = 1.8\ M_\odot$, an effective temperature $T_* = 8200$ K, and a bolometric luminosity $L_* \approx 11.3\ L_\odot$. R_* is then $\approx 1.7\ R_\odot$. We assume that the condition for an annulus in the disk to be sufficiently optically thick to re-emission is that $\tau = 1$ at the peak of the νF_ν spectral energy distribution at the temperature, $T_{\rm disk}$, of that annulus. $T_{\rm disk}$ is estimated using the temperature distribution for a flat reprocessing disk given by Kenyon & Hartmann (1987). For the stellar parameters of β Pictoris, the wavelength of maximum disk emission, $\lambda_{\rm max}$, is in the 40-200 μm region for disk radii between 1 and 10 a.u.

The maximum susceptibility to warping occurs when the disk is only just optically thick. The surface density for this can be estimated from $\lambda_{\rm max}$ once the opacity is specified. We consider three forms for the dust opacity; those used by Rowan-Robinson (1986), Ossenkopf (1993), and Menśhchikov & Henning (1997, who show all three in their Fig. 15). Using these functions, kindly provided to us by Dr Menśhchikov, the critical surface density in dust, $\Sigma_{\rm crit}$, for the disk to be optically thick is shown as a function of radius in Fig. 1. There is reasonable agreement between the various opacities in the region of interest.

In addition to the uncertain opacity, there is a larger uncertainty arising from the possible changes in the dust properties within the disk. For example, agglomeration of the dust into larger particles could drastically reduce the opacity. We crudely allow for this by keeping the gas to dust ratio, $f_{\rm g}$, as a free parameter, so that the total surface density at the optically thick to thin transition is $\Sigma_{\tau=1} = f_{\rm g}\Sigma_{\rm crit}$. A large $f_{\rm g}$ then implies a depleted dust opacity.

The radial extent of radiatively induced warping may then be estimated as follows. We assume that there is some timescale, $t_{\rm clear}$, available for the development of a warp as the disk becomes optically thin, and that the outer optically thick annulus of the disk is unstable to warping by equation (5) as this transition is reached. Requiring that $t_\Gamma < t_{\rm clear}$ for $\Sigma = \Sigma_{\tau=1}$ then fixes a maximum radius, $R_{\rm warp}$, for a given $f_{\rm g}$ and $t_{\rm clear}$. This is shown for $t_{\rm clear} = 10^5$ and 10^6 yr in Fig. 1, again for the three opacity functions described above. As expected, there is a fairly strong dependence on $f_{\rm g}$ - a high gas to dust ratio severely restricts the radial extent of possible warping. However, for a clearing timescale of 0.1-1 Myr, and $f_{\rm g} \sim 10^2$, we find that a warp of 10-40 a.u. extent should develop, consistent with it being the progenitor of the observed warped disk around β Pictoris.

4. NON-LINEAR DEVELOPMENT OF THE WARP

To verify these estimates we have computed the evolution of the warp numerically. The code used is identical to that described by Pringle (1997), except for the inclusion of a variable radius beyond which the disk is optically thin. This radius is computed from the surface density using the form for $\Sigma_{\rm crit}$ shown in Fig. 1, and assuming $f_{\rm g} = 10^2$. The viscosity is taken as $\nu_1 = \nu_2 = \nu_{10} R^{3/2}$, implying a steady-state surface density profile, $\Sigma \propto R^{-3/2}$, of the form adopted in 'minimum-mass' solar nebula models (Weidenschilling 1977, Hayashi 1981, for a review see Lissauer 1993). Taking $\nu_{10} = 1.5 \times 10^{-6}$ cm$^{1/2}$s^{-1} ensures a disk mass within 250 a.u. of $\sim 0.1\ M_\odot$ and an evolutionary timescale of ~ 1 Myr, consistent with observations of T Tauri stars (Beckwith et al. 1990; Strom 1995). We use 150 radial and 120 azimuthal grid points, with the radial mesh logarithmically spaced such that the outer edge is at 250 a.u. The stellar mass and luminosity are taken from Lanz, Heap & Hubeny (1995). The disc is initially flat except for a small, seed warp of less than one degree in the outer regions, with a steady-state accretion rate of $10^{-7}\ M_\odot$yr^{-1}. This disk is then allowed to drain freely onto the star.

Fig. 2 and Fig. 3 summarize the results. After around 7 Myr, a warp is excited at an initial radius of around 5 a.u. The growth is rapid on the scale of the Figure, as the growth timescale at this radius is much less than the viscous timescale at the outer edge. The warp steadily diffuses outwards, with a complicated pattern of growth occurring in the inner regions. The excitation of the warp lasts for a few Myr, during which time a large peak tilt develops in the inner 10 a.u. As was found in the calculations presented by Pringle (1997) the disk tilt remains a smooth function of radius throughout – i.e the disk does not become so twisted as to lose its integrity. Tests at a variety of numerical resolutions show variations in the disk evolution in the strongly non-linear regime, this calculation shows a typical result but cannot be regarded as a prediction of, say, the maximum inclination attained. The large uncertainties in $\nu(R)$, $\eta(R)$, $\tau(R)$, and the complicating effects of a disk with significant scale height, reinforce that conclusion.

Once the disk has become optically thin, the warp decays on the viscous timescale. Fig. 3 shows the profile of the warp after ~ 6 Myr of decay, when the warp of the inner few 10's of a.u. is $\sim 5 - 10$ degrees. At this stage the disk is not tightly 'wound-up', and is decaying with a simple warp. The inner regions for which the viscous timescale is shorter have already flattened themselves out, and the warp decays smoothly towards the outer disk edge. For this surface density profile, with $\Sigma \propto R^{-3/2}$, the relatively small reservoir of mass at large radii is unable to ultimately flatten the disk back into its original plane. At the end of the calculation, the disk is thus close to flat but tilted with respect to its original plane.

5. DISCUSSION

In this Letter, we have discussed the possibilities for radiation driven warping of protostellar disks. We find that as a result of the high optical depth of the inner disk at typical accretion rates, the disk should be unstable to warping at late times, when the accretion luminosity is negligibly small compared to that of the star. The warp is excited in the optically thick inner disk, and is most severe there, but spreads to a range of radii.

The development of a warp is a strong function of the stellar luminosity, and hence mass. As the luminosity increases, warping should set in at progressively higher accretion rates. Twisted inner disks may be a partial cause of the lack of the usual accretion disk signatures in Herbig Ae-Be stars, and could lead to anomalously high extinction towards stars that are actually several Myr old.

For the Sun, the protosolar luminosity is expected to be too low for warping to occur before planet formation was well underway. This is consistent with the approximate coplanarity of planetary orbits. Around more massive stars, of several solar masses, the disk lifetime is shorter, and the higher luminosity means that the instability occurs at higher accretion rates. This mechanism could then lead to non-coplanar planetary systems around massive stars.

Applying this model to a β Pictoris type star, we find that the disk should have become warped at the time when the inner disk reached the optically thick to thin transition, and that the radial extent of the predicted warp is a few 10's of a.u. Numerical calculations confirm these estimates, and suggest that the warp at its peak might have been severe. Moreover, the final plane of the disk may not coincide with that of the stellar equator. In this scenario, the current small warp seen in β Pictoris could be the decaying remnant of a previously much more severe twist induced by the radiative instability.

Since the prevailing explanation for the warp in the β Pictoris disk appeals to a large planet on an inclined orbit (Burrows et al. 1995), it is worth commenting on the differences between this scenario and that presented in §3. Our work suggests that warps should occur in dusty disks around luminous stars; whether it can be applied to the specific case of β Pictoris depends on the star's age. If the system is of the order of 10^8 years old (Burrows et al. 1995; Brunini & Benvenuto 1996), then a planet is a plausible mechanism to maintain the observed warp. Conversely, if β Pictoris is only ~ 12 Myr old, as inferred by Lanz, Heap & Hubeny (1995), then no planet is required to explain the current warped disk. Weak support for a young age is provided by observations of the analog system HR 4796A, which is inferred to be ~ 8 Myr old (Stauffer et al. 1995).

This model predicts that warps should be common in the inner regions of protostellar disks at late epochs, with the largest and strongest warps occurring in disks around high luminosity stars. Warping can only be avoided if either the disk becomes optically thin to re-emission at higher accretion rates than is currently favored, or the dust opacity at late times is severely depleted.

Although few systems may be as fortuitously aligned for observations as the disk in β Pictoris, the changes in the scattering properties implied by warped disks may be detectable in a larger sample of young stars.

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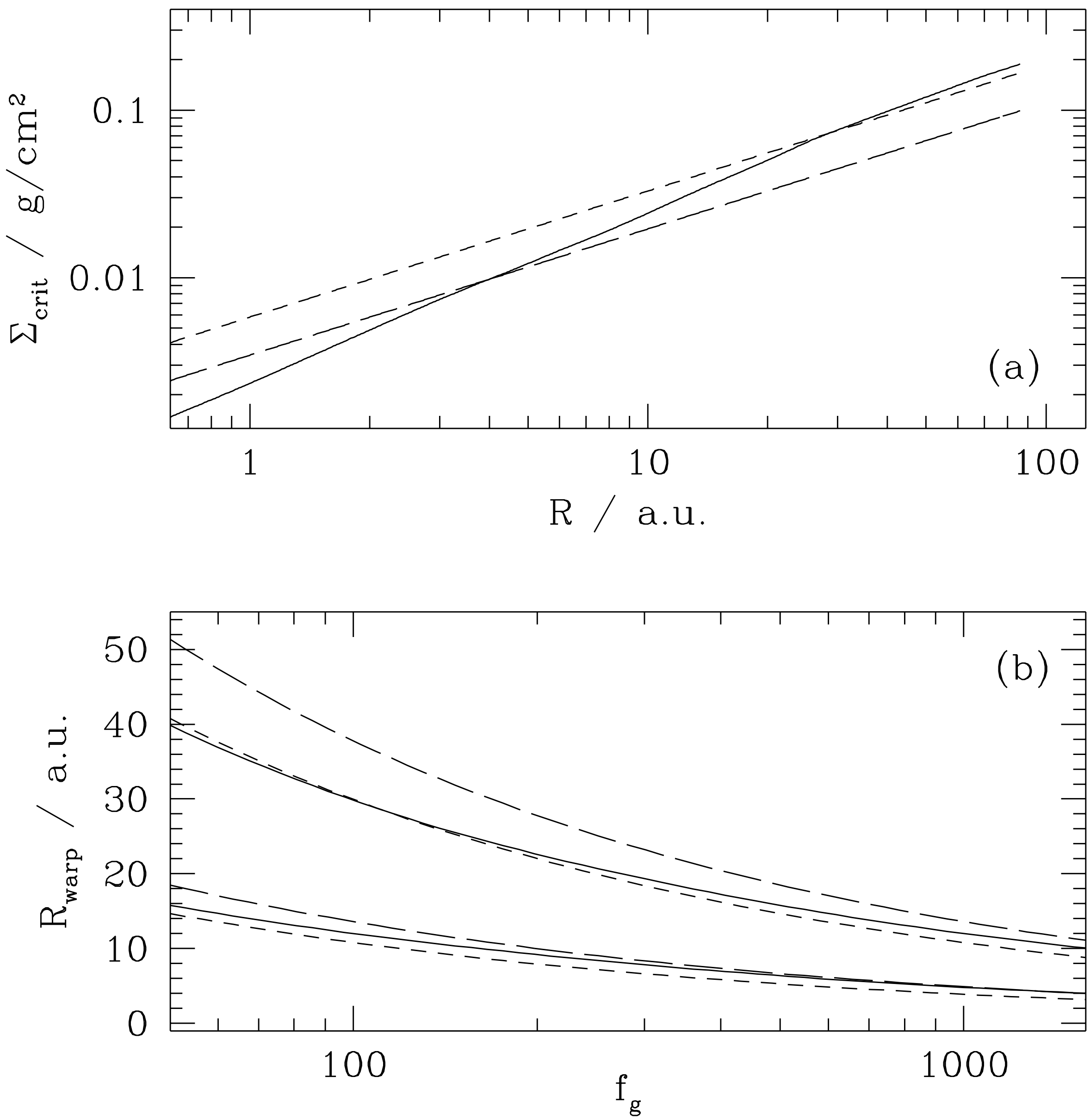

Fig. 1.— Properties of a disk surrounding a β Pictoris-type star at an earlier stage of its evolution. (a) The critical surface density *in dust* required for the disk to be optically thick to re-emission of stellar radiation, for three dust opacities described in the text. (b) The radial extent of the warp, assuming that the time available for the warp to grow as the disk becomes optically thin is 10^5 yr (lower curves), or 10^6 yr (upper curves), as a function of the gas to dust ratio $f_{\rm g}$.

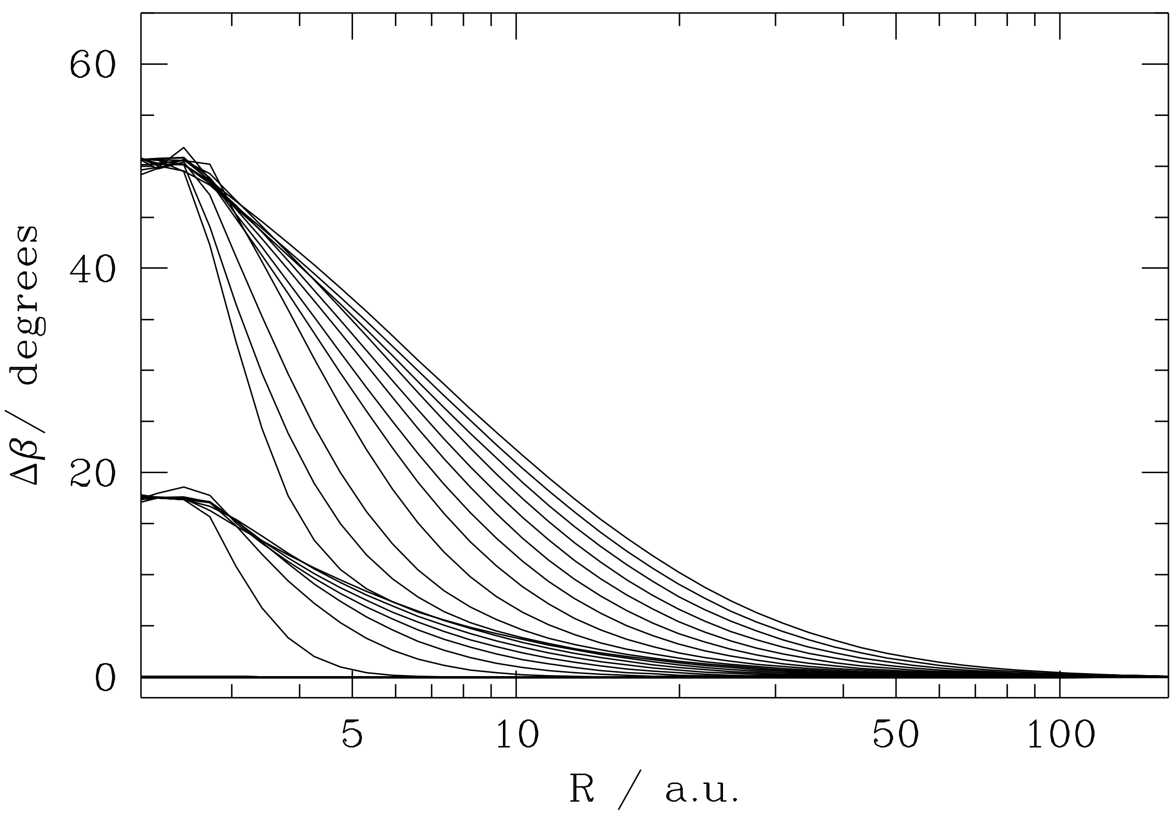

Fig. 2.— The tilt of annuli in the disk, relative to the outermost annulus at 250 a.u., during the initial growing phase of the instability. Curves are plotted at 0.5 Myr intervals, for 2Myr.

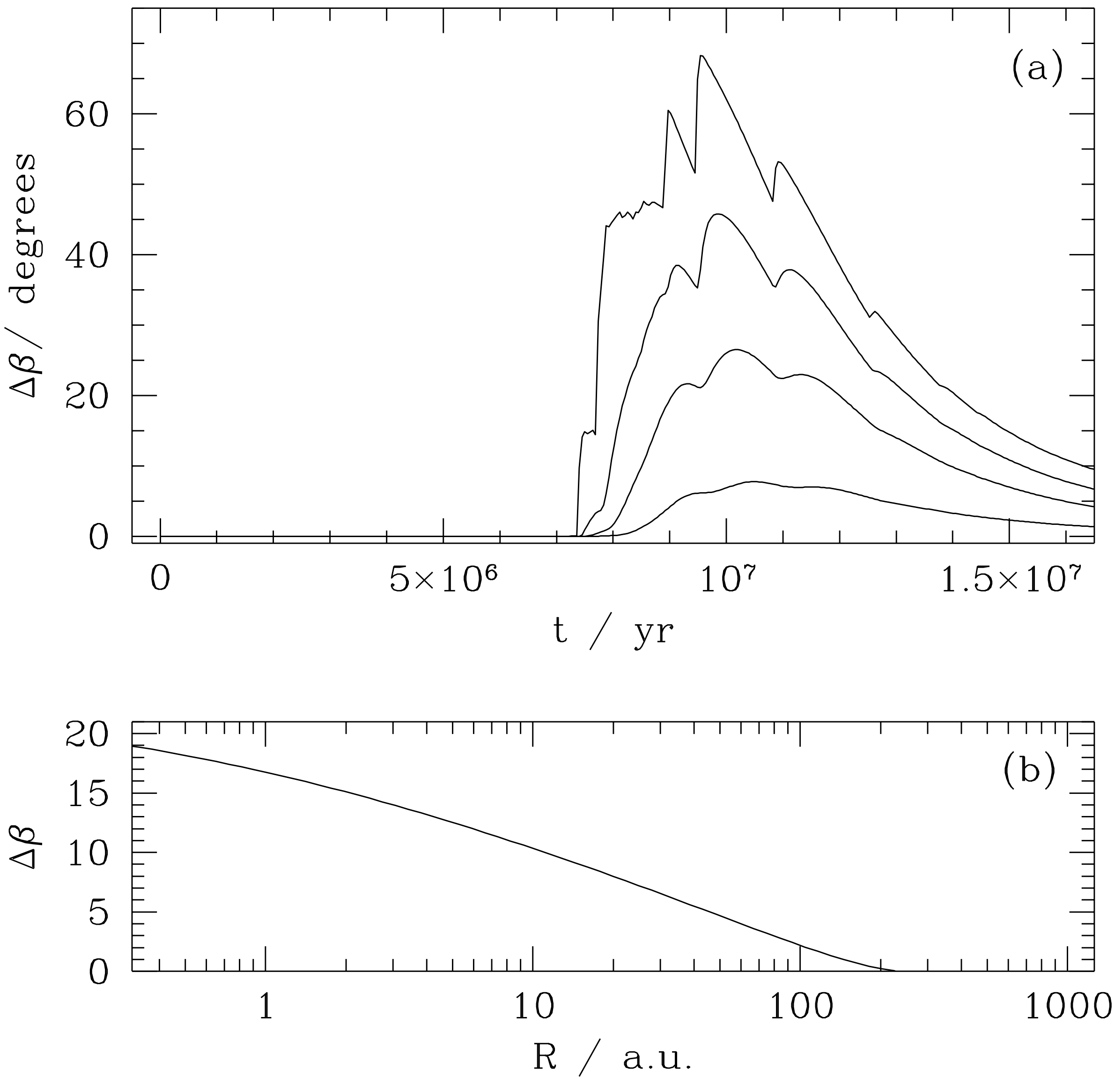

Fig. 3.— (a) The angle of tilt $\Delta\beta$ of annuli in the disk, relative to the outermost annulus at 250 a.u. From top downwards, the annuli are at 3, 10, 30 and 100 a.u. (b) The tilt of the disk as a function of radius at $t \approx 1.6 \times 10^7$ years, well after radiative excitation of the warp has ceased.